# Seismic Propagation in the Baikal Rift Zone: A Transition from a Craton to an Orogenic Zone

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## ABSTRACT

Most nuclear tests occur on continents. Continental geology can broadly be separated into stable shields and orogenic zones. Recently it has been recognized that large variations in the seismic properties of the upper mantle occur beneath the continents and these need to be taken into account when using seismograms to discriminate explosions from earthquakes, to measure seismic yield and to locate events. This report documents lateral variation in attenuation, anisotropy, and seismic velocity in a 1200x1500 km area centered on the Baikal rift zone in Siberia, based on two portable array experiments we carried out with colleagues from University of Wisconsin and the Institute of the Earth's Crust, Irkutsk in the summers of 91 and 92 as well as analog regional network data collected in 94 which we have digitized. The attenuation analysis finds that relative $t^*$ has a 0.1 second anomaly at the rift zone and increases to the east into the Sayan-Baikal fold belt. Explosions detonated in this area would have reduced body wave amplitudes at arrays at teleseismic distances such as NORESS with a concomitant underestimate in yield. We have observed S wave splitting of on average 1 s at virtually every station, implying that significant anisotropy is present in the uppermost mantle. Though fast directions are spatially coherent in local regions there is significant variation region to region. Travel time delays shown an unusual pattern of a central peak of about 1 sec surrounded by two troughs of about 0.5 secs. We attribute the combination of low Q, anisotropy and travel time anomalies to small scale convective upwelling beneath the rift zone. Comparison with similar experiments and the global Earth models is taken as evidence that these effects are present worldwide beneath orogenic zones on the continents and should be taken into account as part of any global seismic monitoring system.

(Mantle Anomaly Attenuation Anisotropy Baikal Continental Rift Zone)

## OBJECTIVE

The objective is to study the propagation of seismic waves in a region of anisotropy and lateral heterogeneity using digital data that we, along with colleagues from the University of California, Los Angeles (UCLA), University of Wisconsin (UW), and the Institute of Earth's Crust of Russian Academy of Sciences at Irkutsk (IEC) collected in the summers of 91 and 92 in south central Siberia and Mongolia, and local array network data collected in the summer of 94. Continental rifts lie in regions of some of the largest lateral heterogeneity in velocity and attenuation in the continental crust and mantle. It is therefore important for nuclear monitoring purposes to quantify how seismic waves are affected by such lateral heterogeneities so that estimates of yield and location are accurate, and source type discrimination is reliable.

## RESEARCH ACCOMPLISHED

### Introduction

This report is a continuation of previous ones [Davis et al., 1992; Gao et al., 1994a; 1994b; 1994c; Gao, 1995] on seismic propagation in the Baikal rift zone (BRZ) of Siberia and in northern Mongolia. During the last year we added to our data set by digitizing (Nxscan) analog seismograms from 27 stations of the Russian S. Siberian network (Figure 1), in order to extend the area over that covered by our portable array installations. Data from our experiments have been submitted to the Iris Data Management Center[Davis et al., 1992; 1993a; 1994].

The Baikal rift zone extends 1500 km along the transition from the stable Siberian platform to the Sayan-Baikal mobile fold belt (Figure 1). It is the most seismically active continental rift in the world. Lake Baikal contains 1/5 of the world's fresh water, with the maximum depth 1600 m. The maximum width of the lake is about 50 km. The sediments are up to 6 km deep [Zorin, 1971; Logatchev and Florensov, 1978].

Various lines of geophysical evidence suggest the asthenosphere upwarps beneath a broad region surrounding lake Baikal giving rise to a significant lateral heterogeneity in the upper mantle. At the lake, the crust thins. The combination of thinned lithosphere and crust, and a graben filled with a thick layer of sediments affects the propagation of seismic waves at most of the frequences of interest for nuclear monitoring. Active and ancient failed rift structures are found on every continent. It is therefore important to establish their deep structure and document its effect on seismic waves from nuclear explosions, including tests that might be carried out in a rift zone which, because of its absorptive properties, may disguise yield.

### Effect of P-Wave Attenuation on Yield of a Rift Zone Explosion

We calculate relative $t^*$ using a spectral inversion method developed by *Halderman and Davis* [1991] for P wave coda from the 1991 array [Gao et al., 1994b]. Figure 2 shows the spatial distribution of $t^*$ across the profile W to E. A localized $t^*$ anomaly of 0.1 seconds occurs at the lake with an increase of 0.05 seconds to the east (where $t^*$ is the relative attenuation). The results are consistent with the pattern published by Murphy et al [1993] who find high $t^* = 0.60$ in the region about lake Baikal with an increase of 0.05 to 0.065 to the southeast. Thus in the vicinity of the lake the total $t^*$ reaches 0.7, i.e., among the highest values in Eurasia. We calculate that estimates of yield from a rift zone nuclear explosion based on body waves at NORESS [e.g., Ringdal 1990] would be 70% too low because of attenuation.

## Interpretation of Teleseismic P-wave Travel Time Residuals

The data consist of 2128 P-wave travel times from 155 teleseismic events, corrected by subtracting theoretical arrival times [from the IASPEI 1991 Earth model, Kennett and Engdahl, 1991]. Relative residuals were formed for each event by subtracting the event's mean residual from the raw residuals and detrended to isolate velocity anomalies having wavelengths less than the array length (1260 km).

To examine the dependence of the relative travel time residuals on event location, we group the events into 26 groups by azimuth ($\phi$) and epicentral distance ($\Delta$) of the sources. This gave 517 mean travel time residuals from 26 groups which were then used in an inversion for structure.

Most of the event clusters recorded by the 1992 profile (Figures 3) display a peak in their travel time residual curves approximately in the region -30 km $< x <$ 60 km with troughs on either side. A similar structure is seen in the attenuation data (Figure 2). The peaks are interpreted to arise from upwarped low-velocity structure associated with convective upwelling in the mantle. The relatively uniform distance between the valleys, and the large shift in their location as a function of incoming azimuth are interpreted to be caused by two high velocity structures located about 200 km deep.

We used both isotropic and vertically anisotropic upper mantle models to interpret the travel time data [Gao, 1995]. The models have a curved lithosphere/asthenosphere boundary that upwarps beneath the rift and in the isotropic model downwarps on the flanks. For the isotropic model the asthenosphere upwarps from 200 km to about 45 km. The magnitudes of the downwarps are about 120 km in the west and 40 km in the east. The velocity contrast between the lithosphere and the asthenosphere is about -2.4% (Figure 4).

The anisotropic model has an asthenospheric upwarp from 232 km to about 42 km with a velocity contrast of -2.7% . At the base, the upwarp is about 260 km wide. The maximum vertical anisotropy is 2.8% (Figure 4) and decays exponentially away from the rift.

## SKS Splitting Measurements and Interpretation

The ubiquity of SKS splitting [e.g., Kind et al, 1985; Silver and Chan, 1988, 1991; Silver and Kaneshima, 1993; Gao et al., 1994a; Liu et al., 1995; Gao, 1995] strongly suggests that variations in anisotropy need to be included in models of upper mantle propagation. It is generally believed that the main cause for SKS splitting in the mantle is flow-induced preferred orientation of crystallographic axes of elastically anisotropic minerals such as olivine. SKS splitting measurements are shown in Figure 5 which is divided into 4 zones A-D based on the tectonics (A: rift- shear zone, B: rift, C: craton, D: Fold belt). The splitting ranges from 0.3 to 2.1 seconds consistent with a layer of 30 to 210 km thick characterized by 4% anisotropy.

In area $A$, the fast directions are scattered with an average approximately ENE-WSW. Five stations in area $B$ (B01-02, B07, B17, and B24) near the rift axis show NE fast directions, i.e., parallel to the surface expression of the rift and the strike of the two dimensional low velocity structure. Most of the rest of the stations show fast directions perpendicular to the rift axis. The rapid change of the fast directions on station B17 and B18, which are 30 km apart, may indicate that the source of anisotropy in the area is shallow, at a maximum depth of 100 km, as revealed by the Fresnel zone forward modeling [Gao, 1995]. Any deeper the spatial variation at the surface would be more spread out.

The fast direction in area $C$ is dominantly NW-SE which is perpendicular to the rift axis. In the northern part of area $D$, the fast directions are dominantly perpendicular to the rift axis, while at the transition to the fold belt in northern Mongolia, fast directions change to nearly E-W, i.e. parallel to the faulting and fold axis. The transition takes places between stations D07 and D09, over a distance of about 90 km suggesting a source for the transition in the upper few hundred km.

Mobility of olivine crystals at temperatures above 900°C is high and therefore the survival of fossil anisotropy is very unlikely at about 150 km and deeper beneath PreCambrian platforms such as the Siberian Craton [Vinnik et al., 1992]. Beneath present-day continental rifts such as the BRZ, the 900°C isotherm is thought to upwarp to a depth of about 50 km [Zorin and Osokina, 1984]. The thickness of the layer cooler than 900°C ('rigid layer') is about 50 km in the vicinity of the BRZ. Near the rift axis (in area B), the thickness of the rigid layer is too small to generate the observed splitting, if all the anisotropy is fossil anisotropy. Therefore at least part and probably most of the observed splitting must originate in the asthenosphere sustained by mantle flow. The fast direction for the southern part of the profile is roughly E-W which is consistent with the dominant direction found across the Tibetan Plateau [McNamara et al., 1994]. Both the Tibetan and the Mongolian Plateaus have been deformed by Cenozoic deformation related to the collision of India with Asia. The observed fast directions in both regions may have the same origin.

### A Small-Scale Mantle Convection Model for the Baikal Rift Zone

Based on these observations a small-scale mantle convection model is constructed (Figure 6). According to the model, there is an asthenospheric upwarp in the vicinity of the BRZ. The low velocity upwarp starts approximately at the base of the lithosphere, which has a thickness of about 200 km and reaches the base of the crust. The flow induces anisotropy orienting a, b, and c axes of olivine crystals as shown in figure 6. In the vicinity of the rift zone, vertical flow dominates; In the areas away from the rift zone the dominant flow direction is horizontal and perpendicular to the rift axis. Further testing of this model is in progress.

## CONCLUSIONS AND RECOMMENDATIONS

Convection in the mantle beneath continents brings hot material from depth which has the effect of lowering P and S wave velocities as well as Q, and inducing anisotropy. As a result, estimates of yield based on body waves could be as much as a factor of three too low for events detonated above such an upwelling current. Global tomography maps [Woodhouse, 1995 in Press, personal communication] indicate such low velocity regions are common beneath orogenic zones on the continents. Accurate location of nuclear events will eventually have to take both lateral heterogeneity in velocity from such thermal effects as well as effects from anisotropy induced by the flow. Seismic anisotropy can result in converted phases, and has strong effects on surface waves [e.g., Park et al., 1994]. Further work needs to be done on this unique data set, including searching for Lg blocking, characterizing effects on surface waves, S wave attenuation and travel times and receiver function analyses.

This work provides a calibration for extension to other orogenic continental regions where global models (of order 20) have insufficient resolution, but geophysical signatures such as gravity, topography, heat flow as well as tectonic history could be used to infer lateral variations in the upper mantle, thereby extending the global models. The resulting model of the continents would then serve as a basis for inverting seismograms from potential test sites for location and yield, when monitoring a CTBT.

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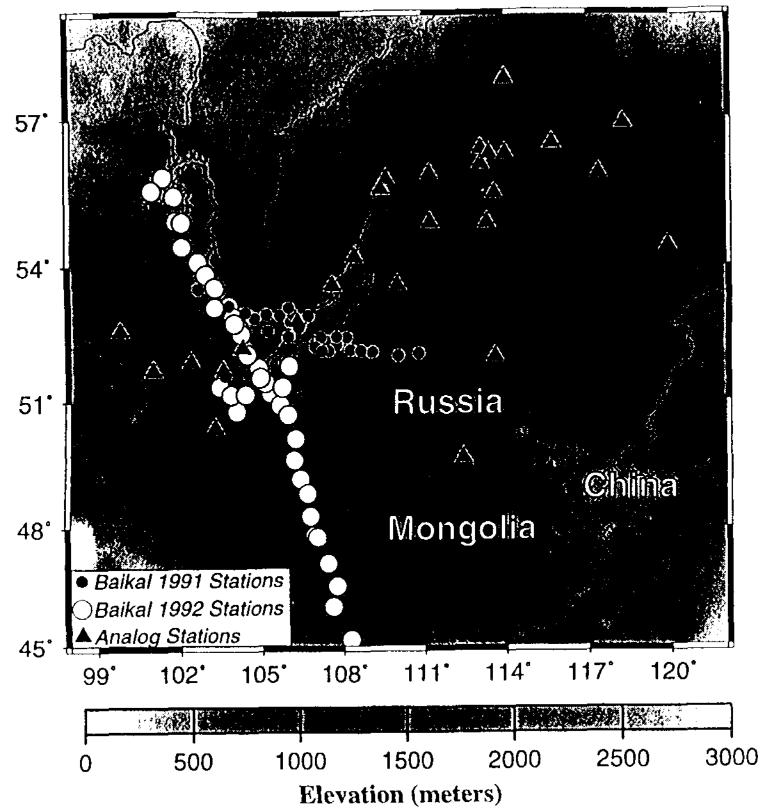


Figure 1: A Mercator projection map showing location and type of stations used and topography of the area under investigation. Elevations are part of the global ETOPO-5 data set and are smoothed with a two-dimensional boxcar filter.

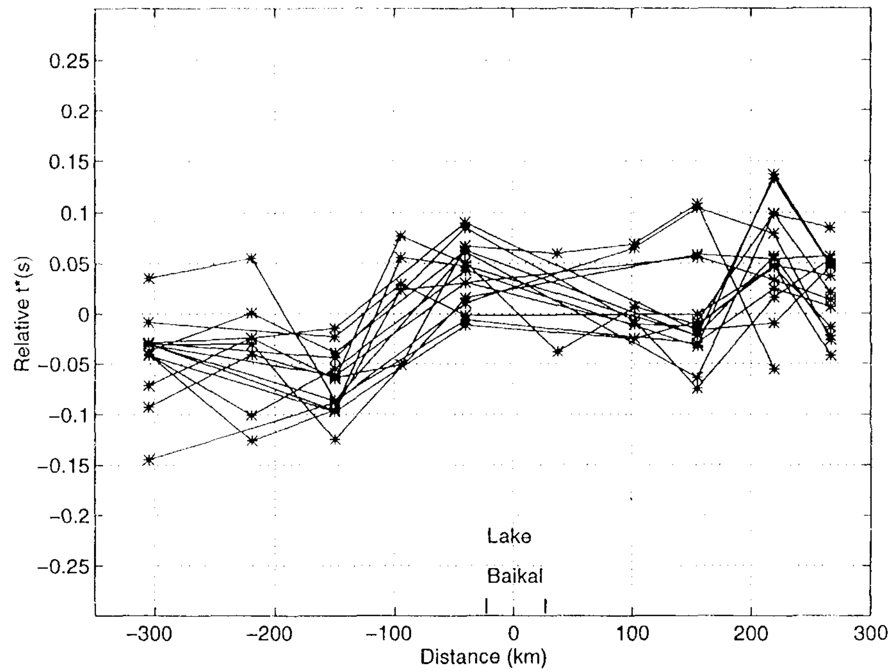


Figure 2: Spatial distribution of t* along the 1991 profile estimated from 13 events. Note the greater attenuation beneath Lake Baikal. Zero on the horizontal coordinate corresponds to the center of the lake [Gao et al., 1994b].

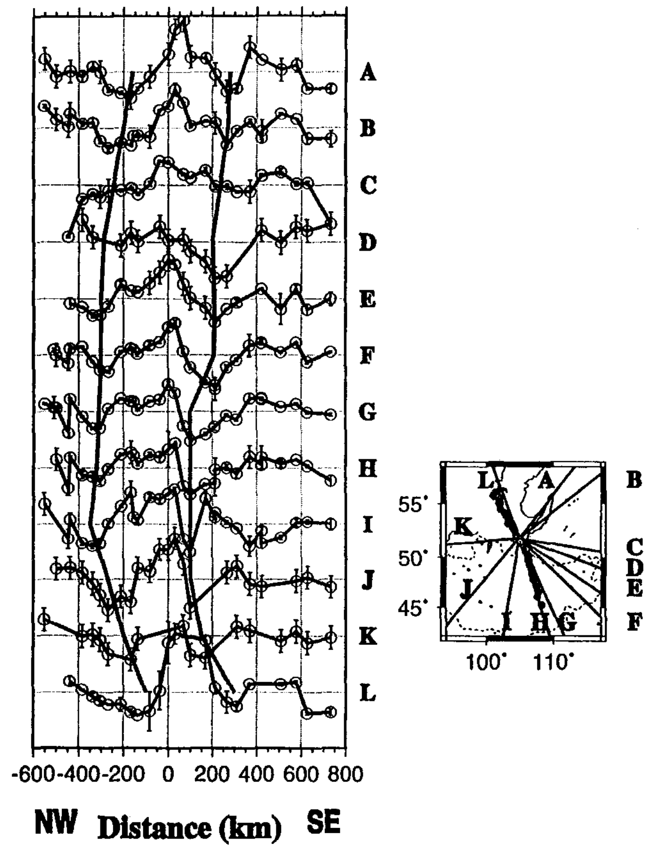


Figure 3: Mean travel time residual curves from the 1992 array event groups. Each vertical unit represents one second. Each horizontal grid line is the zero line of a group, with group name written on the right side of the diagram. The two vertical curves connect the location of the two minima on the residual curves. The insert on the right shows average arrival direction of each event group.

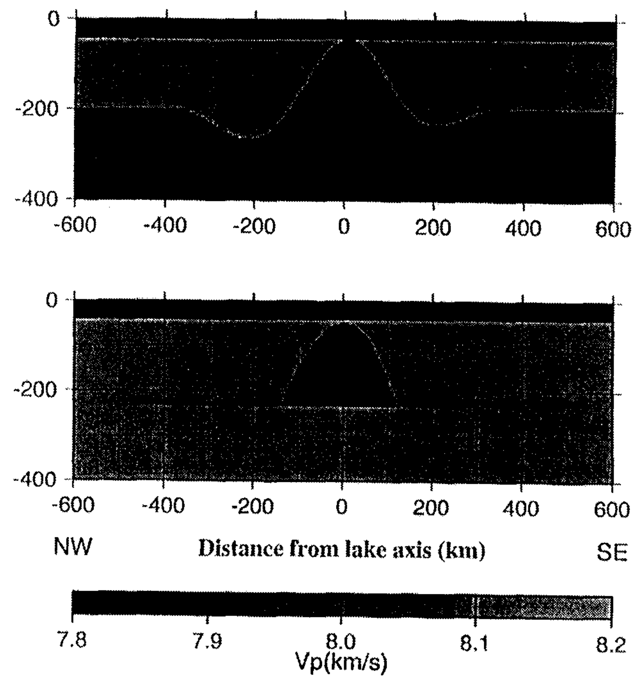


Figure 4: Isotropic (top diagram) and anisotropic velocity model determined from Bayesian non-linear inversion of the travel time residuals.

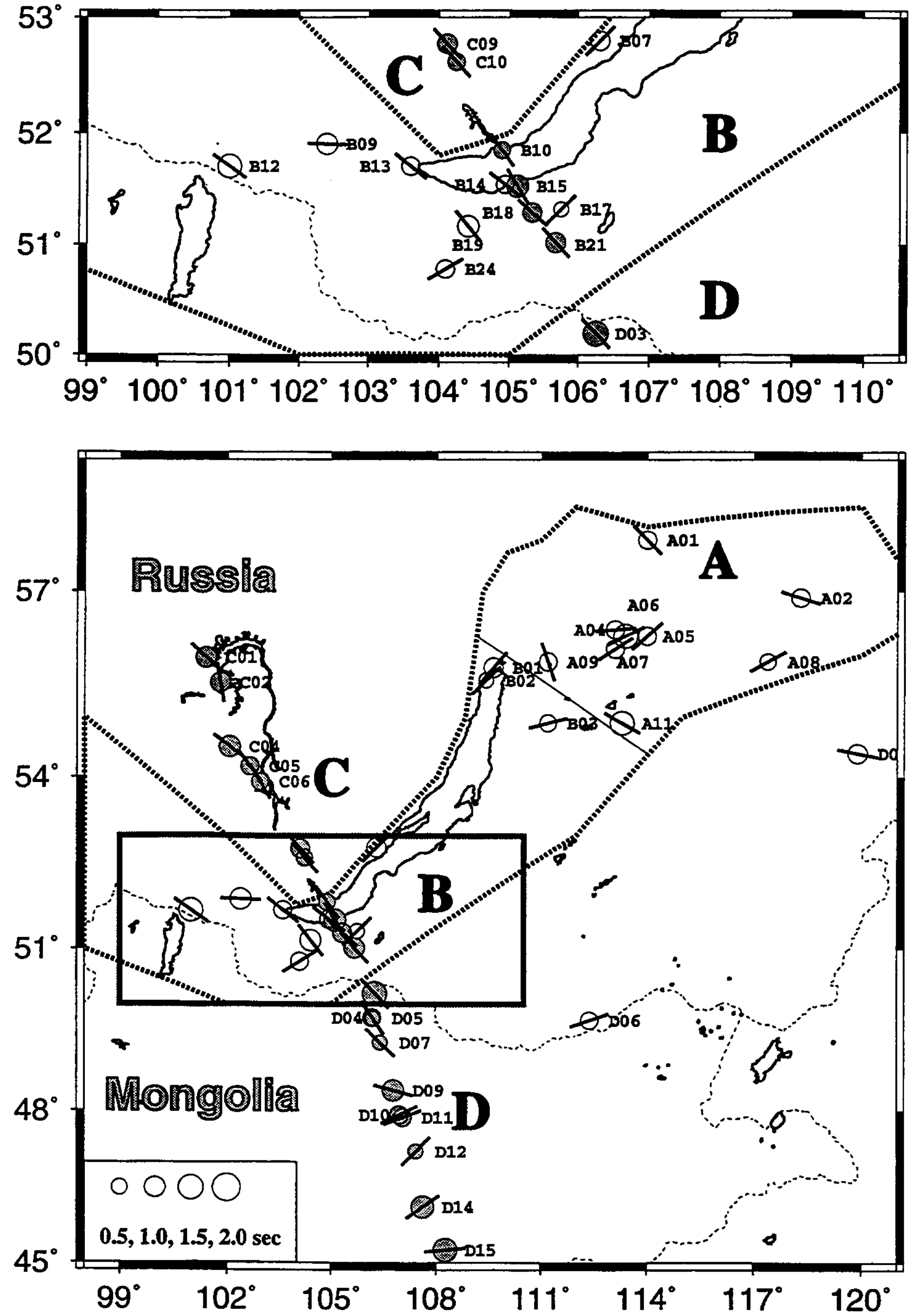


Figure 5: Maps showing SKS splitting measurement results. The diagram on the top is an enlargement of the rectangle in the lower diagram. Stations with well-defined measurements are represented by single circles with size proportional to the splitting. The line drawn through each circle gives the fast polarization direction.

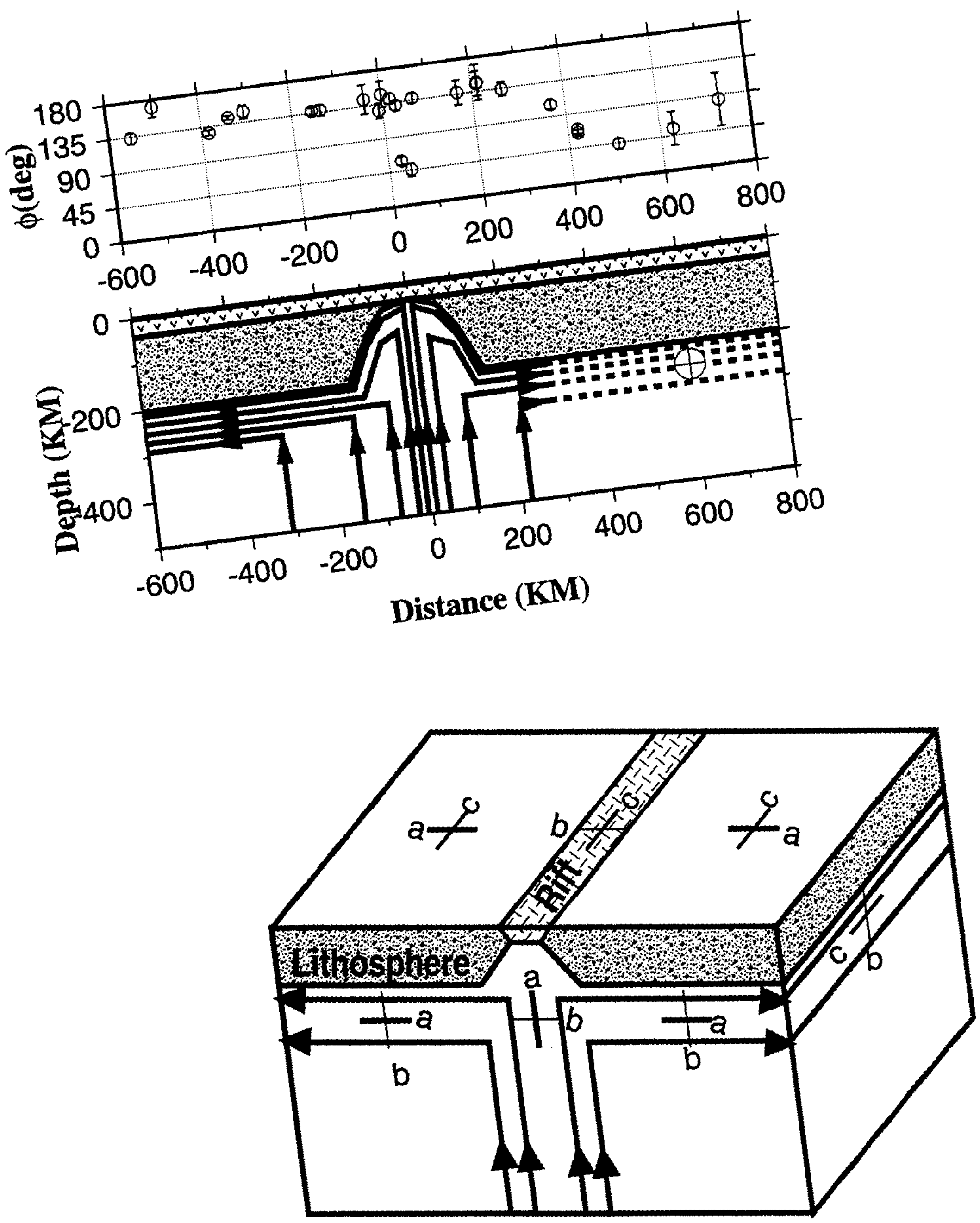


Figure 6: A small-scale convection model for the Baikal rift zone (middle diagram), fast SKS directions along the 1992 profile (top diagram), and orientation of olivine (a-fast, b-slow, c- intermediate) crystallographic axes in vertical and horizontal mantle flows (bottom diagram).